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Multi-hazard response analysis of a 5MW offshore wind turbine

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Abstract

Wind energy has already dominant role on the scene of the clean energy production. Well-promising markets, like China, India, Korea and Latin America are the fields of expansion for new wind turbines mainly installed in offshore environment, where wind, wave and earthquake loads threat the structural integrity and reliability of these energy infrastructures. Along these lines, a multi-hazard environment was considered herein and the structural performance of a 5 MW offshore wind turbine was assessed through time domain analysis. A fully integrated model of the offshore structure consisting of the blades, the nacelle, the tower and the monopile was developed with the use of an aeroelastic code considering the interaction between the elastic and inertial forces, developed in the structure, as well as the generated aerodynamic and hydrodynamic forces. Based on the analysis results, the dynamic response of the turbine's tower was found to be severely affected by the earthquake excitations. Moreover, fragility analysis based on acceleration capacity thresholds for the nacelle's equipment corroborated that the earthquake excitations may adversely affect the reliability and availability of wind turbines.

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Keywords: offshore wind turbine; multi-hazard environment; aeroelastic code; earthquake excitations; time-domain analysis; fragility curves

1. Introduction

Wind energy already prevails in the field of the so-called “green energy production” [1]. China, India, Korea and Latin American countries constitute areas of large expansion for new wind turbines mainly installed in offshore environment, where an exposures' set consisting of wind, waves and currents along with earthquake excitations may increase the vulnerability of wind turbines [2]. Hence, from a structural engineering perspective, it is of high

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importance to safeguard the reliability and structural integrity of wind turbines during their foreseen lifetime (20-25 years). The latter triggered the motivation for the current study, within which a 5MW offshore wind turbine of 110 m total height was subjected to a multi-hazard environment including the conventional environmental loading, i.e., wind, waves and current loads, along with the earthquake-induced excitations. The accurate representation of the dynamic wind and wave fields and the use of numerous earthquake ground motions were enabled by utilizing an aeroelastic code that allows for the time domain analysis of an integrated wind turbine model consisting of the rotor blades, the nacelle, the supporting tower and the monopile foundation. The interaction among the elastic and inertia forces, developed in the offshore structure, and the generated aerodynamic and hydrodynamic forces and damping was also simulated, while a time-dependent pitch control system enabled elaborating the structural performance of the wind turbine under varying operational conditions, i.e., parked, operational and emergency shut-down status. Such a holistic approach followed herein (integrated framework for both the wind turbine and the set of the concurrent exposures) is expected to favor the objectives of the current study, which are summarized as follows:

- quantitative assessment of the multi-hazard environment and the corresponding dynamic response of the 5MW offshore wind turbine subjected simultaneously to different sets of wind, waves and earthquake motions; and
- fragility analysis to evaluate the vulnerability of the wind turbine and especially its highly sensitive and expensive equipment, located at the nacelle, due to the adverse effects of the multiple exposures.

2. 5 MW Offshore Wind Turbine

2.1. Reference structure

The 5MW NREL wind turbine, used herein, has been already treated by several researchers as a reference structure for analytical studies of contemporary multi megawatt onshore and offshore wind turbines. Figure 1 presents briefly the main characteristics of the specific wind turbine model, while an extended description of its geometrical, material, structural as well as mass properties can be found in Refs. [3-4].

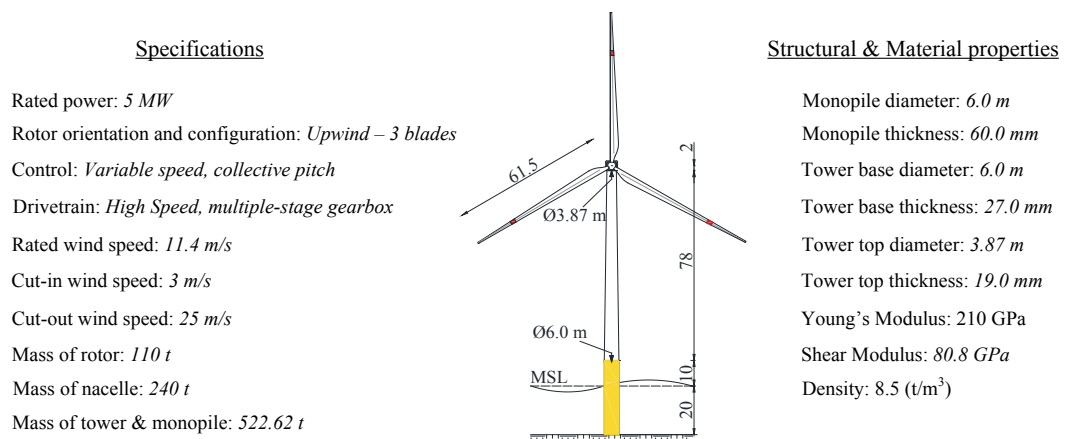


Fig. 1. The 5 MW reference offshore wind turbine.

2.2. Aero-servo-elastic model of the 5 MW offshore wind turbine

The use of advanced aeroelastic codes, being dedicated to the modelling, analysis and design of wind turbines, is nowadays favored when the complex dynamic response of these energy-harvesting infrastructures is pursued. Employing the HAWC2 code [5], a nonlinear, aero-servo-elastic model of the reference wind turbine can be generated and time domain analysis enables calculating, with increased accuracy, the structural performance of the offshore structure. The multibody dynamics simulation facilitates modelling all the critical components of wind turbines (i.e., monopile foundation, tower, nacelle, rotor, shaft and blades) as a series of continuous, flexibly or

rigidly interconnected discrete “bodies” preserving reasonably low number for the required degrees of freedom. Each body is an assembly of Timoshenko beam elements accounting for their conventional properties, e.g., bending and shear stiffness, while higher meshing refinement is commonly applied for the turbine’s components with varying geometry along their length (blades and tower). Geometrical nonlinearity is also considered and hence, large deformations of the structural bodies can be efficiently captured. Regarding the aerodynamic simulation, the HAWC2-embedded model is based on the blade element momentum (BEM) theory extended, though, from its conventional approach to account for dynamic inflow, dynamic stall, skew inflow and shear effects on induction. Taking advantage of the HAWC2 advancements described above, a fully integrated model of the 5MW offshore wind turbine was created consisting of the monopile, tower, shaft, hub and the three blades. The latter were simulated with Young’s modulus equal to 13.10GPa , while detailed geometrical data can be found elsewhere [3]. Fixed-based model was adopted herein, since the monopile was considered to be driven into soil profile of high stiffness. However, the soil flexibility and the related soil-foundation-superstructure interaction phenomena have been found of high relevance for the wind turbines’ dynamic performance especially in case of soft soil conditions [6-7]. Eigenvalue analysis was conducted via HAWC2 for the reference turbine and the tower’s first mode frequency (fore-aft) was calculated equal to 0.276Hz . More details about the dynamic characteristics of the reference model are available in Ref. [3]. Regarding the damping, recent studies found that parked wind turbines experience low damping, i.e., 0.5%-2% of the critical damping, while the aerodynamic damping amplifies the overall damping for an operational wind turbine up to 5% or even higher [8,9]. The Rayleigh damping, accounting for the stiffness and mass contributions, was considered herein and for the parked case, structural damping ratios of 0.48 % and 1% were adopted for the blades-and-tower-related modes [3,10]. Moreover, a control system (servo) model, which was implemented within the HAWC2 computational framework by external Dynamic Link Library (DLL) files, enabled regulating the variable-speed pitch-regulated wind turbine in the nonlinear simulations.

3. Multi-hazard Environment and Time-domain analysis of the 5 MW Offshore Wind Turbine

Using the HAWC2 code, the wind field can be defined in terms of a random, 3D turbulence field, which is discretized on a rectangular grid. The main deterministic contributions for the wind field definition include the mean wind velocity (at the hub-height), \bar{U} , the turbulence intensity and the wind shear profile, assumed to follow a power law. The stochastic properties of the turbulent wind field are defined on the basis of the Mann’s uniform shear spectral model, suitably modified to account for non-isotropic atmospheric conditions. The Mann model, prescribed by the IEC 61400-1 standard [10], is governed by three parameters: (i) Γ is a non-dimensional anisotropy parameter, (ii) $a\varepsilon^{2/3}$ is a measure of energy dissipation, and (iii) L is the length scale of the Von Kármán energy spectrum, which serves the basis for the Mann model definition. Moreover, the wave loads are defined on the basis of an irregular sea state approximated by the superposition of the linear regular waves propagating with a range of phases, frequencies and amplitudes. The energy distribution among the multiple linear wave components is quantified via the Jonswap spectrum. The latter is governed by the significant wave height, H_s , the wave period, T_p , and the peak enhancement factor, γ , that determines the spectrum’s sharpness. The definition of the wave field enables calculating the hydrodynamic loads for the immersed structural components and hence, the Morison’s equation is applied, where both inertia and drag contributions are considered.

Earthquake loads, represented by natural ground motions, were considered also for the time domain analysis of the reference offshore wind turbine. Acceleration time histories, recorded during past seismic events, excited the base node of the structural model using an appropriately developed DLL file that enables accounting for external forces and deformations into the HAWC2 aeroelastic code. The appropriateness of using the seismic module of HAWC2 to perform time domain seismic analysis has been already verified by undertaking an extensive validation scheme [11]. A multi-criteria strategy was applied to select 40 pairs of horizontal components of ground motions obtained from the PEER-NGA Database. A large variety of seismological characteristics (moment magnitude and epicentral distance) as well as ground motion and site parameters (amplitude, duration, frequency content and soil conditions at the recording sites) is associated with the selected motions reflecting the seismotectonic conditions of various locations worldwide. Detailed description of the selected seismic motions can be found in Ref. [11]. The

definition of the multi-hazard environment along with the finite element modelling of the offshore wind turbine enabled the performance of nonlinear time domain analyses in HAWC2 via numerical integration (Newmark's method). It is noted that current velocity of 1.0 m/s was also considered for the time domain analysis, while the simulation length was set equal to 600 s with the seismic motions starting at the 300 s to ensure that the earthquake-induced vibration occurs as the structural response has attained a steady state [12].

Besides the already defined wind, wave and earthquake exposures, the multi-hazard response of the 5 MW offshore wind turbine model was investigated accounting for three operational scenarios (OS):

- (i) OS1 – The wind turbine is normally operating under the earthquake-induced strong ground motion excitation, while operational wind-wave loads are considered. Especially, the mean wind velocity (at the hub-height) and the significant wave height were taken equal to 13 m/s and 6.5 m respectively.
- (ii) OS2 – An acceleration threshold (1 m/s^2) at the nacelle location is adopted and its exceedance due to the concurrent wind-wave-earthquake loading activates the emergency stop. The mean wind velocity and the significant wave height, considered for OS2, are identical to the ones adopted for OS1.
- (iii) OS3 – The offshore wind turbine is considered parked for $\bar{U} = 35\text{ m/s}$ and $H_s = 6.5\text{ m}$. Particularly, the rotation of the shaft is considered fully blocked and the initial pitch angle reaches the maximum that, in turn, corresponds to the minimum exposed area of the blades to the wind stream.

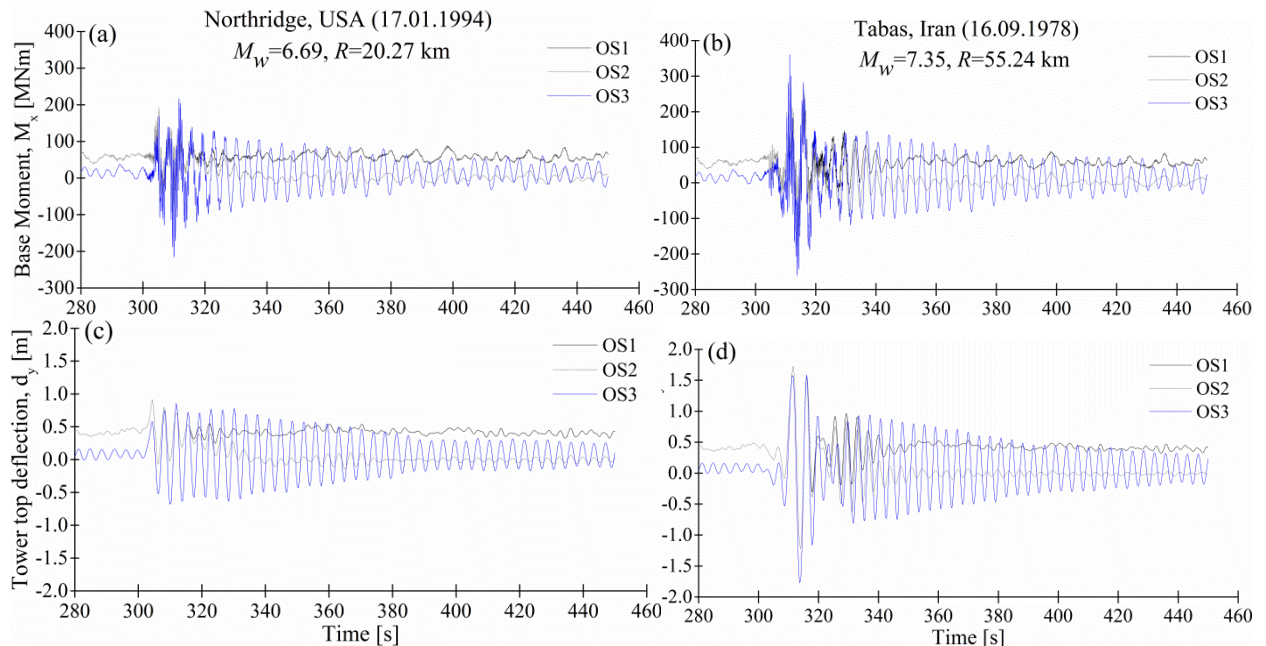


Fig. 2. Response time histories of the 5 MW offshore wind turbine.

Figure 2 plots the dynamic (time-history) response of both the monopile's base (bending moment, M_x) and the tower top (displacement, d_y) of the reference wind turbine when subjected to the multi-hazard environment accounting, at the same time, for the three operational scenarios. It is notable that the earthquake excitations, i.e., the Northridge and Tabas seismic motions, induced significantly higher demand (after the 300 s) than just the conventional wind-and-waves loading (before the 300 s). Similar results have been also found for seismically-excited offshore wind turbines that are supported by both jacket structures and tripods [13]. Especially, due to the earthquake hazard contribution, the M_x and d_y demand parameters of the 5 MW offshore wind turbine, studied herein, were increased, on average, by 496% and 425% respectively. Such a governance of the earthquake effects highlights the necessity to consider the seismic forces for the structural design and assessment of wind turbines located in earthquake-prone areas.

4. Fragility analysis of the 5 MW Offshore Wind Turbine

The wind-waves-earthquakes-induced vibrations at the nacelle's location can either reduce the useful life of the critical and sensitive components mounted there (e.g., electrical generators, inverters, transformers and the gear box) or, in case of high enough accelerations, trigger their direct failure [14]. Hence, fragility curves were analytically derived to identify the vulnerability of several nacelle's components for different earthquake intensity levels, quantified in the current study by the spectral acceleration at the fundamental period of the turbine's tower. Based on the structural reliability theory [15], the fragility is defined as the probability of the structural demand, D , reaching or exceeding a certain capacity limit, C , for a given intensity measure, IM , of the hazardous action. Probabilistic approach was adopted, while the lognormal probability distribution was followed both for the seismic demand and the acceleration-related capacity, the latter was defined herein on the basis of post-earthquake assessment of the condition of non-structural elements and components (i.e., machinery, wall partitions and ceiling, electrical, ventilation and hydraulic equipment) that can be found in industrial or residential buildings [16]. The aforementioned definition of the fragility can be analytically expressed by the following equation [17]:

$$P[D > C | IM] = \Phi \left[\frac{\ln(S_D/S_C)}{\beta_{D|IM}^2 + \beta_C^2} \right] \quad (1)$$

where $\Phi[\bullet]$ is the standard normal cumulative distribution function, S_D and $\beta_{D|IM}$ are the median estimate of the demand and its standard deviation respectively, while S_C and β_C are the median value for the capacity and the related standard deviation. It is notable that the accelerations at the nacelle's height, calculated via time domain analyses of the reference model under the aforementioned set of multiple exposures, was chosen as the demand parameter. It is also notable that the spectral acceleration at the fundamental period of the structure, $S_a(T_1)$, was adopted herein as the necessary intensity measure, IM , for the earthquake hazard.

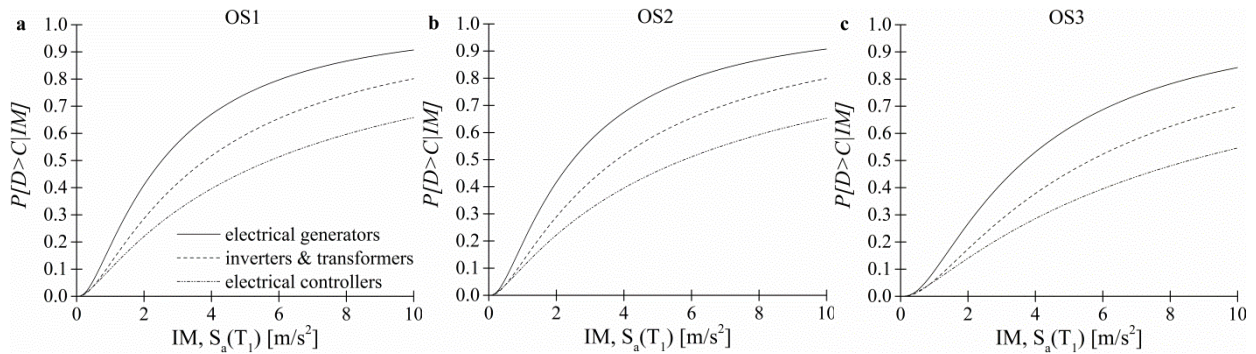


Fig. 3. Fragility curves in terms of the acceleration-based capacity of nacelle's equipment for (a) OS1, (b) OS2 and (c) OS3. The capacity terms have been defined according to Ref. [14]: for electrical generators, $S_C = 8.8 \text{ m/s}^2$ and $\beta_C = 0.50$, for inverters and transformers, $S_C = 11.8 \text{ m/s}^2$ and $\beta_C = 0.60$, and for electrical controllers, $S_C = 15.7 \text{ m/s}^2$ and $\beta_C = 0.80$.

According to Fig. 3, where the acceleration-related fragility curves are plotted, the nacelle's equipment, being critical for the availability and operability of the offshore wind turbine, was found to be less vulnerable to the earthquake hazard when the turbine was considered parked. On the other hand, almost identical vulnerability was found for the two operating scenarios (OS1 and OS2); especially, the probability of exceeding the acceleration-defined capacity for the electrical generators was calculated higher than 50% for earthquake excitation of moderate intensity, i.e., $S_a(T_1) = 0.25 \text{ g}$. The latter implies that the constant operability and availability of offshore wind turbines can be adversely affected due to accelerations-induced damages in the electrical and mechanical equipment, located at the nacelle, even in cases of low-to-moderate seismic intensity. Hence, the increased risk for significant downtime of the wind turbines may induce significant monetary losses to the relevant stakeholders.

5. Conclusions

The multi-hazard response of a contemporary 5MW offshore wind turbine was assessed through the performance of nonlinear time-domain analysis. The use of an advanced aero-servo-elastic code enabled modelling the different components of the reference wind turbine (monopile foundation, supporting tower, nacelle and blades) along with the related elastic and inertia interactions as well as the generated aerodynamic and hydrodynamic forces and damping. A time-dependent pitch control system that regulates the operation of the wind turbine allowed calculating its performance under different operational scenarios (parked, operational and emergency shut-down status). For the reference wind turbine, the structural demand (defined in terms of base moment and tower top deflections) was primarily driven by the earthquake excitations, while the “environmental” loading (wind and waves) was found to contribute significantly less. Moreover, the fragility analysis, conducted on the basis of numerical analysis results, highlighted the relevance of the seismic hazard for the design and assessment of wind turbines. Especially, the highly-tuned and sensitive equipment, typically located at the nacelle, was found highly probable to experience severe damages even for low-to-moderate seismic intensity ($Sa(T_1)=0.25$ g). The latter finding implies that the reliability and constant availability of offshore wind turbines may be severely degraded by such a demanding set of exposures, consisting not only of the conventional wind-and-waves-induced loads but also the earthquake excitations. Last but not least, it should be noted that the fragility analysis, undertaken herein, disregarded the wind turbine’s structural components (i.e., monopile and supporting tower), which, however, are expected to contribute significantly to the vulnerability of the entire system.

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